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Influence of risk factors and past events on flood resilience in coastal megacities: Comparative analysis of NYC and Shanghai

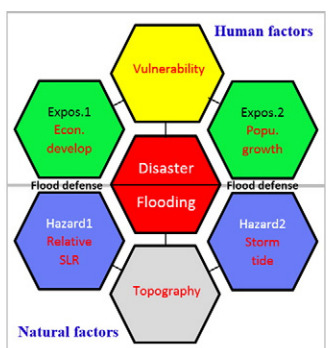
Siyuan Xian [a], Jie Yin [b,*], Ning Lin [a], Michael Oppenheimer [c,d]

[a] Department of Civil and Environmental Engineering, Princeton University, USA
[b] Key Laboratory of Geographic Information Science (Ministry of Education), East China Normal University, China
[c] Department of Geosciences, Princeton University, USA
[d] Woodrow Wilson School of Public and International Affairs, Princeton University, USA

HIGHLIGHTS

- The paper explores why Shanghai has a higher flood protection than NYC.
- Shanghai experiences a higher flood hazard.
- Individual extreme events seem to have made a more direct impact in Shanghai.
- Shanghai is more vulnerable and has a higher exposure at risk.

GRAPHICAL ABSTRACT



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ABSTRACT

Coastal flood protection measures have been widely implemented to improve flood resilience. However, protection levels vary among coastal megacities globally. This study compares the distinct flood protection standards for two coastal megacities, New York City and Shanghai, and investigates potential influences such as risk factors and past flood events. Extreme value analysis reveals that, compared to NYC, Shanghai faces a significantly higher flood hazard. Flood inundation analysis indicates that Shanghai has a higher exposure to extreme flooding. Meanwhile, Shanghai's urban development, population, and economy have increased much faster than NYC's over the last three decades. These risk factors provide part of the explanation for the implementation of a relatively high level of protection (e.g. reinforced concrete sea-wall designed for a 200-year flood return level) in Shanghai and low protection (e.g. vertical brick and stone walls and sand dunes) in NYC. However, individual extreme flood events (typhoons in 1962, 1974, and 1981) seem to have had a greater impact on flood protection decision-making in Shanghai, while NYC responded significantly less to past events (with the exception of Hurricane Sandy). Climate change, sea level rise, and ongoing coastal development are rapidly changing the hazard and risk calculus for both cities and both would benefit from a more systematic and dynamic approach to coastal protection.

1. Introduction

Global megacities are centers of population, business and assets in both developing and developed countries (De Sherbinin et al., 2007). Historically, the prosperity of many of these cities relied heavily on

* Correspondence author.
E-mail addresses: sxian@princeton.edu (S. Xian), rjay9@126.com (J. Yin), nlin@princeton.edu (N. Lin), omichael@princeton.edu (M. Oppenheimer).

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their long-standing seaborne trade with the rest of the world, owing to their advantageous locations near the coast. Coastal megacities are metropolitan areas with a population of over 8 million and with boundaries that are directly exposed to coastal flood risks (Kraas, 2007; Yeung, 2001). Recent extreme floods caused significant physical damage to coastal regions and megacities, e.g., Hurricane Katrina in 2005, Hurricane Sandy in 2012 and Typhoon Haiyan in 2014 (Pielke et al., 2008; Kunz et al., 2013; Xian et al., 2015; Hatzikyriakou et al., 2015; Mori et al., 2014). Sea level rise, land subsidence, and possible changes in storm climatology may cause more flood inundations, and economic losses to coastal megacities in the future (Aerts et al., 2014; Buchanan et al., 2016; Kopp et al., 2014; Lin et al., 2016; Lin and Shullman, 2017; Tosi et al., 2013). Increasing urban exposure further aggravates the situation. Hanson et al. (2011) found that 40 million people (roughly 1 in 10 of the total population in port cities in their study) are currently exposed to 100-year coastal floods. They projected an increase in the exposed population by more than threefold and in exposed assets by more than tenfold worldwide by the 2070s. The dramatically increasing flood risk in coastal megacities calls for immediate actions.

In response, various flood protection measures such as flood walls, barrier systems and levees have been undertaken in coastal cities of both developed and developing countries (Martine and Marshall, 2007). Coastal cities in the developed countries are usually better protected than the ones in developing countries (Hallegatte et al., 2013). Hallegatte et al. (2013) estimated the present and future flood losses for the 136 largest coastal cities and found that only three cities (New Orleans, Miami, and Tampa) among the top twenty in terms of the ratio of annual flood losses to the annual GDP are in the developed world. Many coastal megacities in the developed world that experience frequent flooding, such as London, Amsterdam, Rotterdam, and Tokyo (Dutta, 2011; Hall et al., 2005; Lavery and Donovan, 2005; Morita, 2008; Syvitski et al., 2009; Nicholls and Cazenave, 2010), have high-level flood protection, such as sea walls, storm surge barriers, dike-rings, and super-levees (Kron, 2013; Aerts et al., 2013; Nicholls et al., 2008). In contrast, many megacities in the developing world that are also vulnerable to flooding, such as Guangzhou, Mumbai, and Ho Chi Minh City, still rely on natural protection, such as vegetation.

Among the coastal megacities, New York City (NYC) and Shanghai offer an interesting comparison. First, they are financial centers of the two largest economies (USA and China) in the world, which have quite different governance structures and political systems. Second, both cities have dense population and assets in the floodplain and a long history of tropical cyclones and flooding. Third, inconsistent with the general finding of Hallegatte et al. (2013) that wealthier cities are usually better protected, NYC is currently protected by sandy dunes (e.g., Staten Island), vegetation (e.g., Queens) and bulkheads (vertical retaining walls: e.g., lower Manhattan is protected to lower than the 50-year coastal flood return level) (Fig. 1a). Shanghai has implemented higher-standard measures, including sea walls with a 200-year coastal flood return level design that protect its coastlines and critical infrastructure of the developed areas, sea walls with a 100-year coastal flood return level design that protect less developed regions such as Chongming Island and Fengxian district, and flood walls with 1000-year riverine flood return level along the Huangpu River to protect the city from riverine flooding (Fig. 1b).

A core question arises: what drives policy makers in Shanghai to implement significantly higher-level flood protection than that in NYC? To address this core question, we ask two sub-questions. First, is flood risk of Shanghai higher than that of NYC? While many studies have revealed that each city is at high risk of flooding (Colle et al., 2008; Lin et al., 2010, 2012; Wang et al., 2012; Yin et al., 2013), no direct comparison between the two cities has been made. Second, is policy making on flood protection in Shanghai more sensitive to the occurrence of extreme events? The overall (estimated or perceived) flood risk depends on the historical flood events (Botzen et al., 2009; Small and Xian, 2017). However, individual extreme flood events may or may not trigger immediate responses from policy makers.

To answer these questions, we analyze and compare NYC and Shanghai quantitatively in terms of the natural and anthropogenic risk factors (including flood return periods, topography, societal exposure, and past flood experiences) that have found to influence flood protection measures (Yin et al., 2015; Sayvetz, 2015). We also consider the potential role of governance factors, on-going resilience efforts, and a number of other characteristics of New York and Shanghai from a

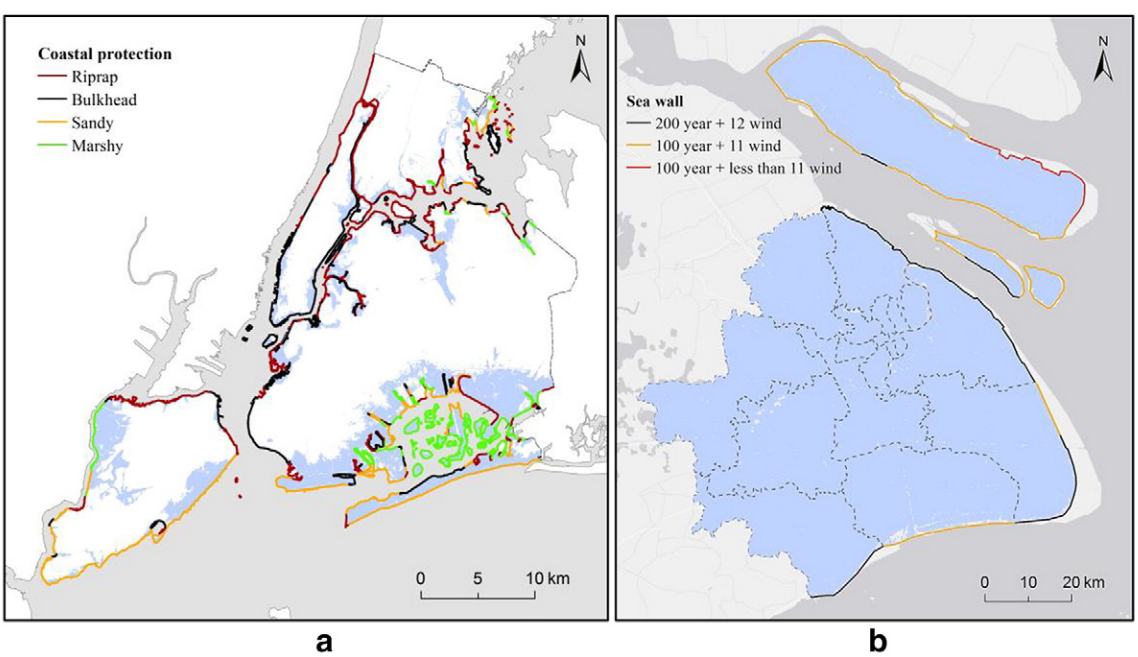

Fig. 1. Spatial distribution of coastal protection measures in (a) NYC and (b) Shanghai. The legend of Shanghai protection, "200 year + 12 wind", means sea wall is built to protect 200-year coastal flooding plus wave induced by 12-force winds. Light blue shade shows maximum inundation extent (with no protection) from Hurricane Sandy (a) and Typhoon Winnie (b).

Table 1
Comparison of Shanghai and NYC in terms of sea level rise, land subsidence, return period of extreme flood events, topography, population increase, and GDP growth.

Elements	Indicators	Shanghai	NYC
Hazard	Sea level rise (mm/year) (filtering land subsidence)	2.6	1.3
	Historical land subsidence (mm/year)	7	1.5
	Current land subsidence (mm/year)	5	1.5
	Current 100-year return level (cm) of storm tide	587	329
	Storm surge height of most extreme event (cm)	257	282
	Current return period of most extreme event (year)	100	1400
Vulnerability	Topography	Low & flat	Mostly high & some low
Exposure	Population growth percentage (%) of last three decades	105.7	15.6
	GDP per capita growth rate (%)	7.1	1.2

qualitative perspective. Our objective is to contribute to a greater understanding of what controls coastal protection strategies and related design-making mechanism.

2. Materials and methods

2.1. Study areas

NYC, centered at 40° 42′ N and 74° W, lies at the junction of the Hudson River and Atlantic Ocean. Shanghai, centered at 31° 8′ and 121° 17′ E, is located at the junction of the Yangtze River and the coastline of the East China Sea. NYC and Shanghai are within North Atlantic Basin and the Northwest Pacific Basin, respectively; both basins experience active tropical cyclones (Fig. 2a and b). The two cities have witnessed frequent storm surge flooding along their extended coastlines (500 km for NYC and 1700 km for Shanghai). The representative tidal-gauge stations, located at the junction of the river and open sea, are the Battery station (40° 42′ N, 74° 0.8′ W) for NYC and the Wusong station (31° 30′ N, 121° 30′ E) for Shanghai (Fig. 2c and d). The total land areas of NYC and Shanghai are 789 and 6340 km^2, respectively. As of 2014, NYC and Shanghai had official recorded populations of 8.5 and 24.15 million, respectively.

2.2. Flood hazards

Flood hazards are characterized by relative sea level rise, past extreme flood levels and return periods of such events based on data from the two representative tide gauges. Sea level and annual maximum water level data of NYC's Battery (1920–2012) come from Tides and Currents of NOAA.[1] Sea level rise and annual maximum water level records for Shanghai's Wusong station (1910–2012) were requested from Shanghai Water Authority by the authors. The data for land subsidence (due to glacial isostatic adjustment, sediment compaction, tectonic subsidence and other local factors; Gornitz et al., 2001; Chai et al., 2004) are based on the previous government reports and scientific literature, specifically: Shanghai Municipal Bureau of Planning and Land Resources (2007), Gong and Yang (2008), Yin et al. (2013) for Shanghai and Sella et al. (2007) and SIRR (2013) for NYC. The relative sea level (RSL), defined as the height of the ocean surface relative to the land, is the sum of the rise of the mean sea level and the subsidence of the local land.

The annual maximum water levels recorded the past extreme flood events induced by different meteorological mechanisms including tropical cyclones, extra-tropical cyclones and other meteorological events. To determine the return period of the past extreme events, flood frequency analysis is conducted using the observed annual maximum water levels. We model the annual maximum water level (after removing the seal-level-rise trend) using the generalized extreme value (GEV) distribution recommended by US. Federal Emergency Management Agency (FEMA) and used in various previous studies to model extreme water levels (Morrison and Smith, 2002; El Adlouni et al., 2007; Xu and Huang, 2011).

We assume that the maximum water level (W) of any given year, as a continuous random variable, has a cumulative distribution function (CDF) as below:

$$P(W \le w) = \begin{cases} \exp\left\{-\left[1+\varepsilon\left(\frac{w-u}{\sigma}\right)\right]^{-\left(\frac{1}{\varepsilon}\right)}\right\}, & \text{if } \varepsilon \neq 0 \\ \exp\left\{-\exp\left(-\frac{w-u}{\sigma}\right)\right\}, & \text{if } \varepsilon = 0 \end{cases} \quad (1)$$

where $u \in R$ is the location parameter; $\sigma > 0$ is the scale parameter and $\varepsilon \in R$ is the shape parameter. The maximum likelihood estimation (MLE) method is used to estimate the three parameters of the GEV distribution and their associated standard errors.

The return period (reciprocal of the annual exceedance probability) of any water level (i.e., storm tide) can then be calculated from the GEV distribution:

$$T_W(w) = \frac{1}{(1-P(W \le w))} \quad (2)$$

The 95% confidence bands of the return period are estimated using the profile-likelihood method (Coles, 2013). This approach for estimating uncertainty in Extreme Value distributions performs well for moderate and small sample sizes (as in our case) (Bolívar et al., 2010).

2.3. Topography and inundation

Digital elevation models (DEM) characterize the topographic features and vertical elevations of NYC and Shanghai. The DEM of NYC, generated by the Light Detection and Ranging (LiDAR) with a grid-cell resolution of 0.3×0.3 m^2, is obtained from the Department of Environmental Protection.[2] The DEM of Shanghai, with a grid-cell resolution of 10×10 m^2, is calculated by interpolating the topographic contours with 0.5 m intervals that were requested from the Shanghai Survey Bureau by the authors (Yin et al., 2013). The vertical error bar of the Shanghai DEM is 0.1 m.

To further evaluate the inundation impact of the most extreme events with the highest storm tide (i.e., Hurricane Sandy of 2012 for NYC and Typhoon Winnie of 1997 for Shanghai and), the possible maximum inundation extent is calculated using the GIS-based static mapping method on the topographic DEM. In this method, the area is regarded as being inundated if its elevation is below the maximum water level and if it is hydraulically connected to open water or flooded regions. This method has been applied in previous studies (e.g., Aerts et al., 2014; Lin and Shullman, 2017).

[1] Data retrieved from https://tidesandcurrents.noaa.gov/sltrends/sltrends_station.shtml?stnid=8518750.

[2] Data retrieved from: https://data.cityofnewyork.us/City-Government/1-foot-Digital-Elevation-Model-DEM-/dpc8-z3jc/data.

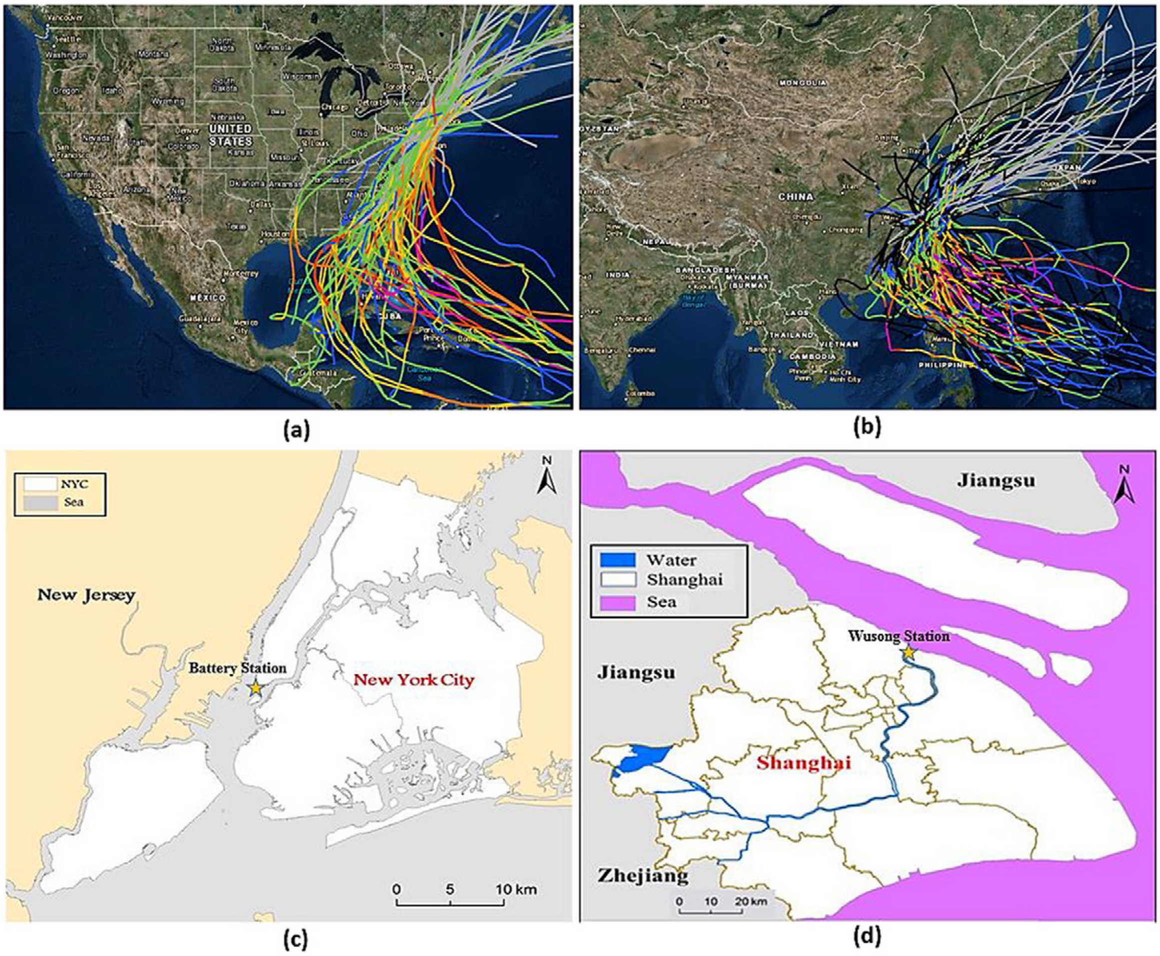

Fig. 2. Geographic locations and historical tropical cyclone tracks of study areas. (a) Historical tropical cyclone tracks (1850–2014) in the North Atlantic basin that passed within 200 km of NYC; (b) historical tropical cyclone tracks (1900–2014) in the Northwest Pacific basin that passed within 200 km of Shanghai; (c) geographic map of NYC; (d) geographic map of Shanghai.

2.4. Urban development and population

To compare urban development over time, we focus on the data for the two cities for the same time intervals (up to 1979, 1980s, 1990s and 2000s). The urban development of NYC is illustrated using the building footprint dataset built by the NYC's Department of Information and Technology[3] that consists of the year of construction and specific locations for over one million building blocks. The urban development of Shanghai is indicated by the land cover and land use maps developed in Yin et al. (2011).

NYC population data come from the 2010 US Census Bureau at the census-tract level, and Shanghai population density data come from the Sixth Nationwide Population Census (2010) with a resolution of 1 km × 1 km. Both datasets were collected through a household-level survey at the highest accuracy. To make the two datasets consistent for comparison, we estimated the population density for NYC at the 1 km × 1 km resolution, through dividing the population by the area (in km^2) of the census tract (assuming the population density is uniform within each census tract).

2.5. Coastal protection

The coastal flood protection data is obtained from the Chapter 3 of the report “A stronger, more resilient NYC” (SIRR, 2013) and previous literature (e.g., Colle et al., 2008) for NYC, and the historical archival of the Shanghai Water Authority (Yu, 1985; Gu, 2005; Yin et al., 2013) for Shanghai. We also evaluated the height of the sea wall for NYC using DEM raster data in Geographic Information System (GIS) and found that the sea wall height matches well with the estimate in Colle et al. (2008).

3. Results

3.1. Risk factors - flood hazards, natural vulnerability and social & economic exposure

The summary of the results for risk factors are shown in Table 1.

3.1.1. Flood hazards - sea level rise, land subsidence, and extreme flooding

NYC's sea level at the Battery station rose at an average rate of 1.3 mm/year (filtering land subsidence) with uncertainty of 0.1 mm/-year over the last 100 years. NYC's land subsidence rate at the Battery station contributed to NYC's sea level rise, with an average rate of 1–2 mm/year (Sella et al., 2007). The sea level rise at the Wusong station in Shanghai rose at an average rate of 2.6 mm/year (filtering land subsidence) over the period of 1910–2000, with an uncertainty of 0.11 mm/-year (for details see Li (1998)). During 1977–2007, the sea level in Shanghai rose 115 mm, at a mean linear rate of 3.8 mm/year, which was higher than the global and national average rate (China Sea Level Bulletin, 2007; Yin et al., 2011). Land subsidence in Shanghai is mainly caused by tectonic subsidence (TS) and compaction of sediments. The rate of tectonic subsidence is 1 mm/year based on the analysis of very long baseline interferometer (VLBI) monitoring data of vertical

[3] Data retrieved from: https://data.cityofnewyork.us/Housing-Development/Building-Footprints/nqwf-w8eh/data).

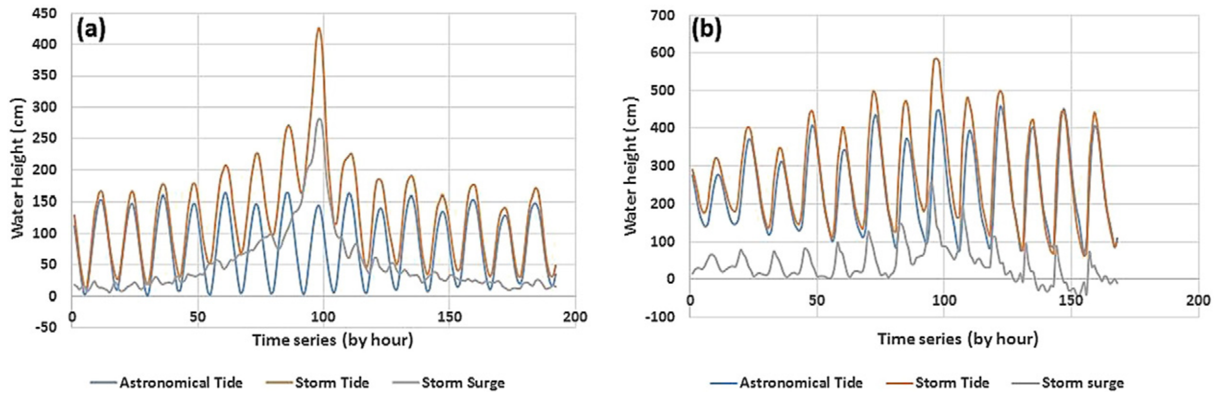

Fig. 3. Hourly time series of astronomical tide, storm tide and storm surge height during (a) Hurricane Sandy in 2012 (NYC) and (b) Typhoon Winnie in 1997 (Shanghai). Data obtained from National Oceanic and Atmospheric Administration (NOAA)'s Tides and Currents for the Battery station, NYC and Shanghai Water Authority for the Wusong station, Shanghai.

movement in the Sheshan bedrock (Qian, 1996). The compaction subsidence (CS) due to withdrawal of groundwater, construction of high-rise buildings and population growth is estimated by a Shanghai geological environmental bulletin (Shanghai Municipal Bureau of Planning and Land Resources, 2007; Gong and Yang, 2008; Yin et al., 2013): the average value of compaction subsidence was nearly 7 mm/year from 2006 to 2010 and 5 mm/year after 2010, likely smaller thanks to an implementation of a policy banning groundwater extraction. Thus land subsidence has contributed significantly to the rise of RSL (the sum of the sea level rise and land subsidence) in Shanghai (Liu and Ye, 2005). Persistence of Shanghai's land subsidence would result in higher local sea level rise compared to that of NYC.

Tropical cyclones and other storm systems such as extra-tropical cyclones can generate storm surge, which is the temporary rise of the coastal water level due to strong onshore winds and atmospheric low pressure. Historically, Hurricane Sandy (2012) and Typhoon Winnie (1997) are the most extreme recorded flooding events for NYC and Shanghai, respectively. The peak surge at the Battery induced by Hurricane Sandy was about 282 cm (Fig. 3a). Typhoon Winnie induced multiple surge peaks, with the highest peak of about 257 cm at the Wusong station (Fig. 3b). Along with peak surge, the arrival time of a storm in the astronomical tide cycle determines the high storm tide (Kemp and Horton, 2013). Both Sandy's and Winnie's peak storm surges arrived at the high astronomical tide, resulting in the highest storm tide on record for the Battery station and the Wusong station, respectively. Given the much higher tidal level in Shanghai (250–400 cm, semi-diurnal vs NYC's 154 cm, diurnal), the peak storm tide level from Winnie was 587 cm, much higher than that from Sandy for NYC (428 cm), relative the respective mean sea level (MSL).

The GEV distribution demonstrates a very good fit to the peak water level data for the two cities (Fig. 4). The extreme value analysis indicates that the return periods of the peak water levels induced by Hurricane Sandy and Typhoon Winnie are approximately 1400 (95% CI: 134, 8.75e6) and 100 (95% CI: 29, 10,543) years respectively, above the "current" 2014 MSL. These estimates are consistent with previous estimation using similar extreme value analysis methods[4] (1570 years for Sandy by Sweet et al. (2013) and Zervas (2013) and about 100 years for Winnie by Yin et al. (2013)). Future sea level rise will increase the annual probability and reduce the return period of extreme water levels. Shanghai's land subsidence rate is higher, resulting in faster reduction in the return periods of extreme flooding events than NYC. Although the estimation of the return period of extreme floods is highly sensitive to the applied statistical/dynamic methods, the same statistical methods used here for the two cities reveal that Shanghai is significantly more likely to experience Winnie-like extreme events than NYC is to experience Sandy-like extremes. Since the land subsidence rate of Shanghai is much higher than NYC due to its tectonic subsidence and rapid compaction rate from human activities expected to continue in the near future (Yin et al., 2013; Gong and Yang, 2008), our comparison is robust at least for the near term. To make the comparison more robust in long-term, we would need to model the local sea level rise (e.g., Kopp et al., 2014) and possibly storm climatology change (e.g., Lin et al., 2012) using more accurate projection approaches.

3.1.2. Natural vulnerability - topography and inundation

Topography can affect the extent and depth of flood inundation and thus indicates the natural vulnerability of a region to flooding (Naess et al., 2015). The low-lying areas of NYC account for a very small portion of the total land that is near the shore (City of New York, 2013). The NYC land areas rise quickly inland to high elevations (over 10 m above MSL), as shown in Fig. 5a. In contrast, Shanghai is largely flat and low-lying, with an average altitude of 4 m above the sea level (Wusong Datum), and its city center is lower than the mean sea level (Yin et al., 2013), as shown in Fig. 5b.

The peak water level during Hurricane Sandy at the Battery is overlaid with three topographic sections (denoted as 1, 2, and 3 in Fig. 5a) across lower Manhattan, Brooklyn, and Staten Island, respectively. The peak water level floods a small portion of the lands near the coast (Fig. 6a–c). We also overlay the peak water level of Typhoon Winnie at the Wusong station on three cross-sections of Shanghai topography (denoted by 1, 2 and 3 in Fig. 5b). The first one goes through the city center, and the other two go through newly developed regions. The three cross-sections of the topography are all below the peak water level (Fig. 6d–f). If the flood protection were not taken into account (to focus on the effect of topography), the potential inundation extent indicates that <10% of NYC would have been flooded by Hurricane Sandy (the blue shaded area, shown in Fig. 1a), while over 95% of Shanghai would have been flooded by Typhoon Winnie (shown in Fig. 1b). Shanghai is more naturally vulnerable to extreme floods than NYC.

3.1.3. Social vulnerability - urbanization, population & economy growth

Exposure of populations and infrastructure, along with the vulnerability of these, determines the magnitude of damage from extreme flooding. The change in exposure largely depends on the urbanization rate, population increase, and economy growth. Limited construction activities have occurred in Manhattan, Brooklyn, and the Bronx since 1979, as shown in Fig. 7a, although zoning changes may have resulted in more building activities since 2013. The construction in Queens between 1990 and 2000 (in red) primarily owes to the renovation of the

[4] Other studies use different methods (e.g. simulation of synthetic storms) and give different return-period values for Sandy (e.g. Orton et al. (2016): 250 years; Lopeman et al. (2015): 100 years).

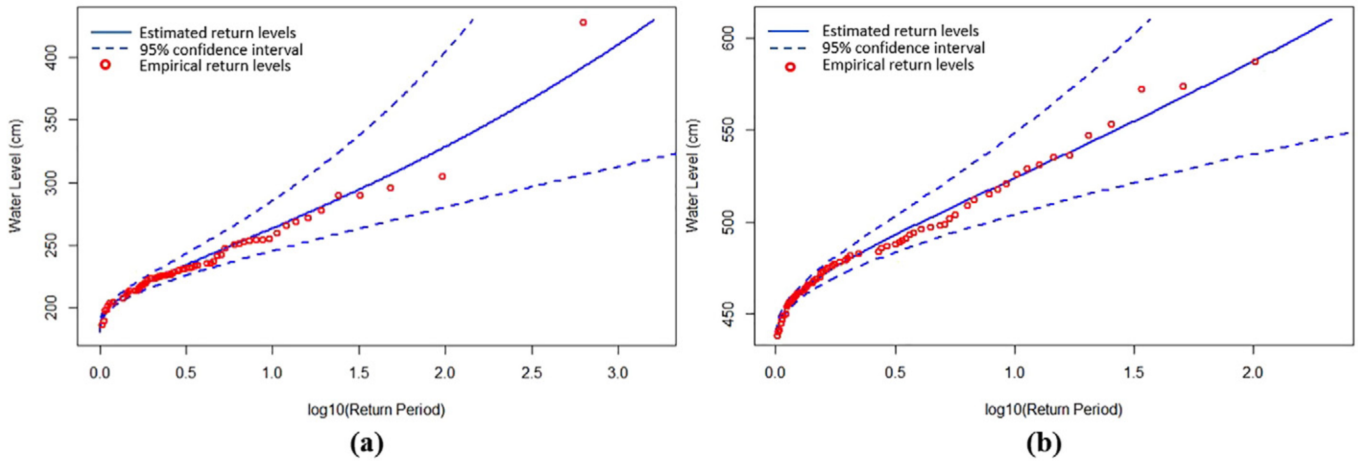

Fig. 4. Estimated return period of water level (cm) for (a) NYC (b) Shanghai, based on observed annual maximum water levels at the Battery station and the Wusong station, respectively.

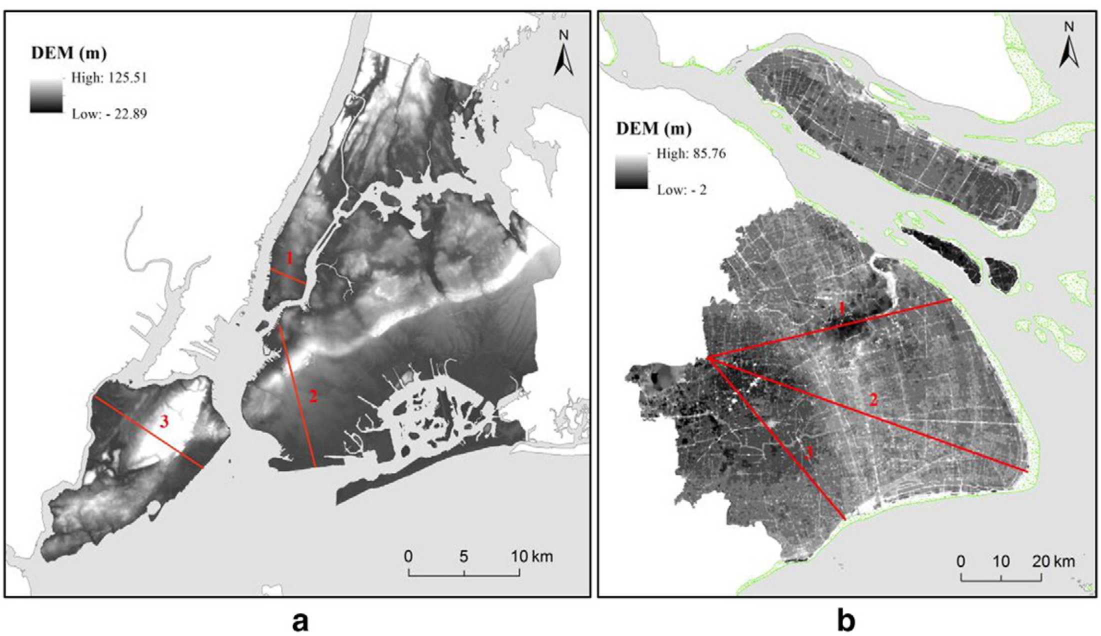

Fig. 5. High resolution digital elevation model (DEM) showing topography of (a) NYC and (b) Shanghai. Three topographic cross-sections for each city (NYC: 1. Lower Manhattan; 2. Brooklyn; 3. Staten Island; Shanghai: 1. through urban center; 2. through Songjiang district; 3. through Jinshan district) are considered in inundation analysis presented in Fig. 7.

John Kennedy International Airport. Overall, the city boundary formed long before 1979 (by 1898), with limited expansion afterwards. In addition, this limited expansion did not concentrate in coastal and low-elevation regions. In contrast, the urban area of Shanghai increased by 1064% from 1979 to 2010 owing to the rapid economic transition and development in China, as shown in Fig. 7b. The majority of the expanded areas were near urban center that is at very low elevation.

Since 1979, Shanghai's population has increased by 110%, which is 7 times that of NYC (15%). Shanghai's population is highly concentrated in the city center (the lowest floodplain of the city; see Fig. 8b) due to population migration from the countryside to urban area during periods of rapid economic transition and development, resulting in more building and infrastructure construction in the vulnerable area. In contrast, NYC's population is more dispersed although the low-lying areas in lower Manhattan have a comparable population density to that of Shanghai (see: Fig. 8a). Thus, the rate of population increase in the floodplain is likely to be much higher for Shanghai than for NYC (although the specific data are not available).

Finally, the average annual increase rate in the GDP per capita in Shanghai (7.1%) is nearly six times that of NYC (1.2%) from 2000 to 2014 based on the data from Brookings Institute.[5] A previous study estimated that the value of coastal exposed assets in the New York-Newark area ($320 billion) is over four times that of Shanghai ($73 billion) in 2005, but by 2070 the exposed assets of Shanghai ($1771 billion) would be close to those of the New York-Newark metropolitan area ($2147 billion) due to rapid infrastructure construction and business development (Hanson et al., 2011). The dynamics (or rate) of fast asset and economic growth in vulnerable parts of the city may provide a strong motive for the government to undertake flood protection policy initiatives and measures. Furthermore, the large migration of the population from rural areas to the city center in Shanghai can further aggravate social vulnerability, including a growth in population with higher vulnerability to flooding (e.g. poor housing conditions, less access to

[5] Date extracted from: https://www.brookings.edu/research/global-metro-monitor/.

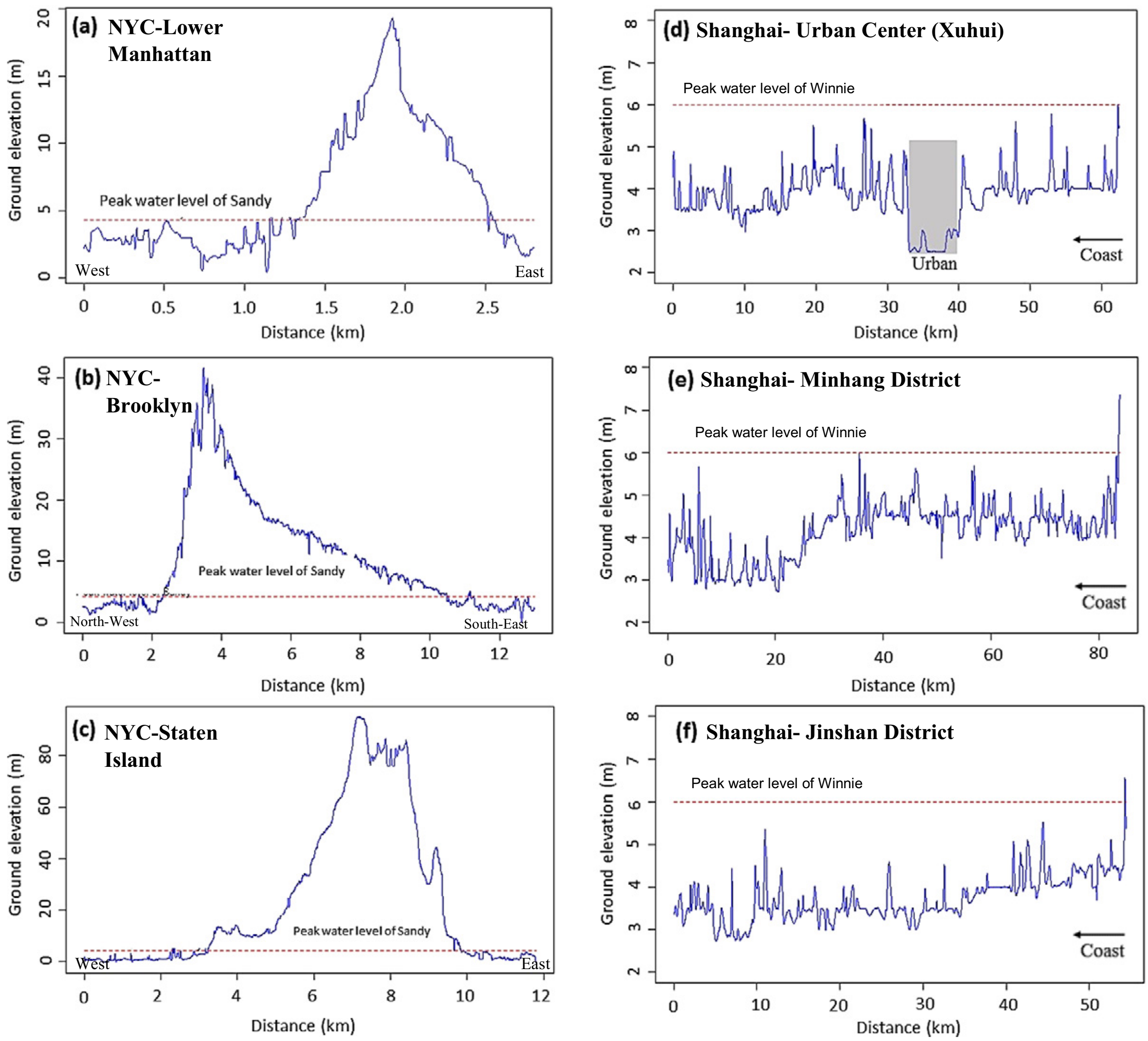

Fig. 6. Topographic effects on flood inundation. (a)–(c) Overlay of topographic cross sections for NYC (a) with peak storm tide level of Hurricane Sandy at the Battery; (d)–(f) overlay of topographic cross sections for Shanghai (b) with peak storm tide level of Typhoon Winnie at the Wusong station.

social insurance programs; see Park and Wang, 2010). The combination of exposure in floodplains due to low topography and asset and population concentration results in rapidly growing exposure to flood risk in Shanghai. Based on these comparisons, we conclude that: Shanghai's overall risk (hazard, topography and increasing exposure at risk) is higher than New York's.

3.2. Past extreme events and flood protection

In addition to the objective measure of risk factors, individual past extreme events may have influenced the immediate reaction of policy makers and can be the driving force for policy measures. Previous literature has discussed how past extreme events may trigger changes in socio-ecological systems (Pelling and Dill, 2010) and policy responses to extreme flooding events (Albright, 2011). However, although past experience plays an essential role (Spence et al., 2011; Shao et al., 2017a), the memories of extreme disasters fade over time (Tobin, 1997; Shao et al., 2017b; Di Baldassarre et al., 2017), implying that if planned or initiated action is not substantially implemented within a brief interval after a disaster, such action may never be completed. In this section, we answer the second sub-question by exploring the linkage between individual extreme flood events and the protection measures. The historical data of extreme flood events and historical archival records for protection measures will be used in our analyses.

Because the Wusong station is at the estuary of the Huangpu River and the East China Sea, the flood wall at Wusong can indicate the standard of both riverine and coastal flood protections for Shanghai. Overlaying the past updates of the flood defense heights on top of the past annual maximum water levels at the Wusong station, we found that each update is associated with an extreme flood event induced by a tropical cyclone (i.e., typhoons in 1962, 1974, and 1981), as shown in Fig. 9a. For example, a severe typhoon in August 1962 hit the city and the generated storm surge flooding that inundated most urban districts, collapsed over 1500 houses, and killed hundreds of people. In 1963, the Shanghai Urban Construction Bureau released the first city-wide flood defense standard, called the “63 standard” that specified the minimum height of the sea wall (4.94 m). On August 20, 1974, Shanghai was inundated again by typhoon-induced flooding with severe damage to residential buildings, factories, and critical infrastructure. Reacting instantly, Shanghai City Flood Control Headquarters announced an enhanced “74 standard” (requiring a design for the 100-year flood level) three months later. Between 1974 and 1981, flood walls with a total length of 158 km were largely reinforced or reconstructed following this new standard. However, from August 31 to September 1, 1981, a strong typhoon (with maximum wind speed of over 33 m/s) induced extensive storm surge flooding and inundated a widespread urban area. Realizing from this event the insufficiency of protection from this event, in 1984, Shanghai Flood Control Headquarters released the “84

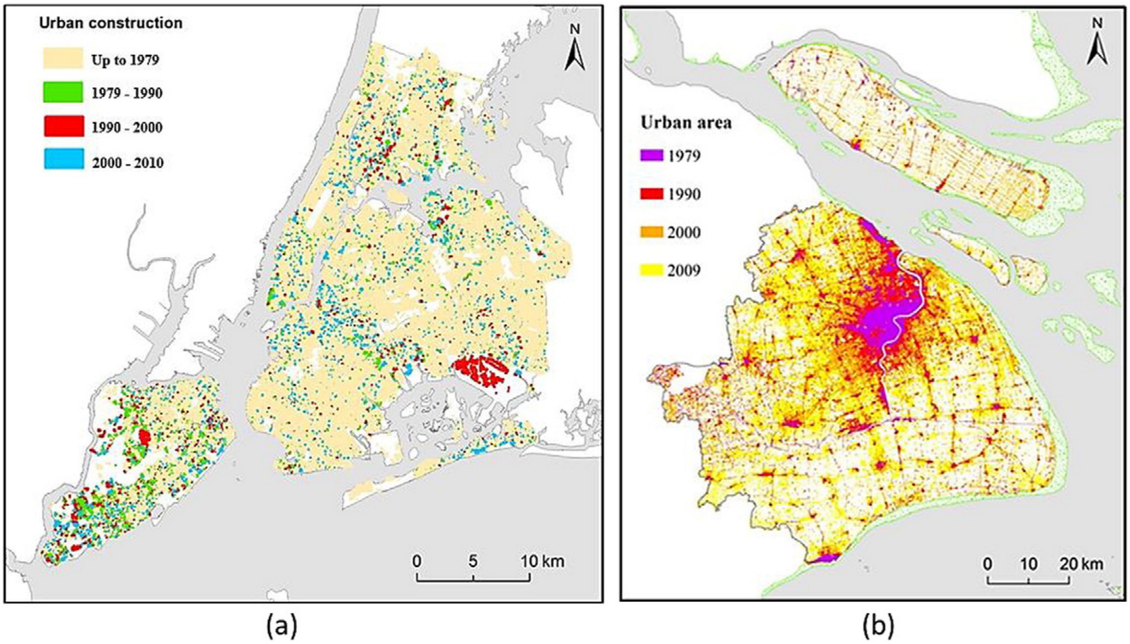

Fig. 7. Historic urban development of (a) NYC and (b) Shanghai.

standard" (requiring a design for the 1000-year flood level) which is still in use today.

Previous extreme flood events of NYC such as the 1938 Long Island Hurricane, Hurricanes Carol and Donna in the 1960s, the Nor'easter of 1972 and Hurricane Gloria in 1985 caused significant damage and drew policy makers' attention with initiatives of coastal protection. For example, after the hurricanes in 1960s, the U.S. Army Corps of Engineers proposed building barriers at Throgs Neck in the Bronx. Later, there were other proposals from the city for a giant gate/barrier at the mouth of Jamaica Bay and a 15-foot reinforced concrete wall throughout the Coney Island. Nevertheless, none of these initiatives have been implemented as of yet. The current coastal protection is still low with, e.g. the height of vertical wall at Lower Manhattan in the range of 1.25 (lower bound)–1.75 (upper bound) meters above MSL (Colle et al., 2008). From the time of the Dutch to modern days, with extensive land reclamation and expansion by depositing landfill in the sea, people simply built up low-rise stone retaining walls (bulkheads) to protect the temporary coastline (SIRR, 2013). The peak water level of Hurricane Sandy stands out in the record at the Battery station, far exceeding the wall height in lower Manhattan (see Fig. 9b) and thus inundated low-lying areas.

The analysis strongly suggests that past individual extreme events had a much more direct and stronger influence on the policy makers' actions on flood protection measures in Shanghai than in NYC. This may be largely due to the larger impact of the extreme events affecting Shanghai, given its low and flat topography. In contrast, NYC suffered relatively moderate consequences from individual events before Hurricane Sandy.

4. Discussions

In addition to evaluation of the risk factors and experience with past events, institutional aspects of governance can play an important role in determining public policy outcomes (Naess et al., 2015). Shanghai, one of the four direct-controlled municipalities under the central government of China, has a higher level of autonomy than other cities that

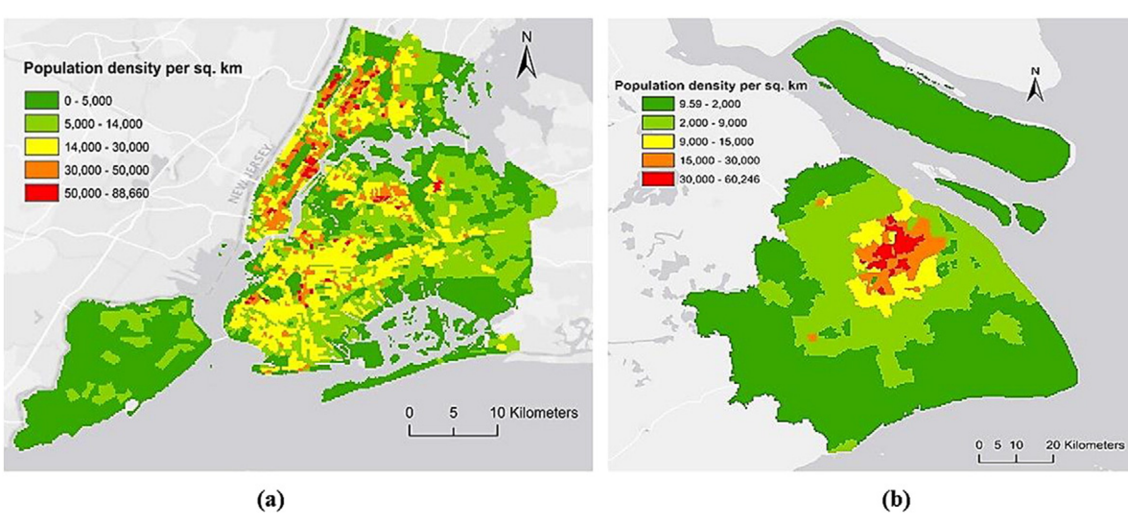

Fig. 8. Population distribution in 2010 of (a) NYC (at 1-km^2 resolution) and (b) Shanghai (at 1-km^2 resolution). NYC population data is from US Census Bureau; Shanghai population data is from the Sixth Nationwide Population Census.

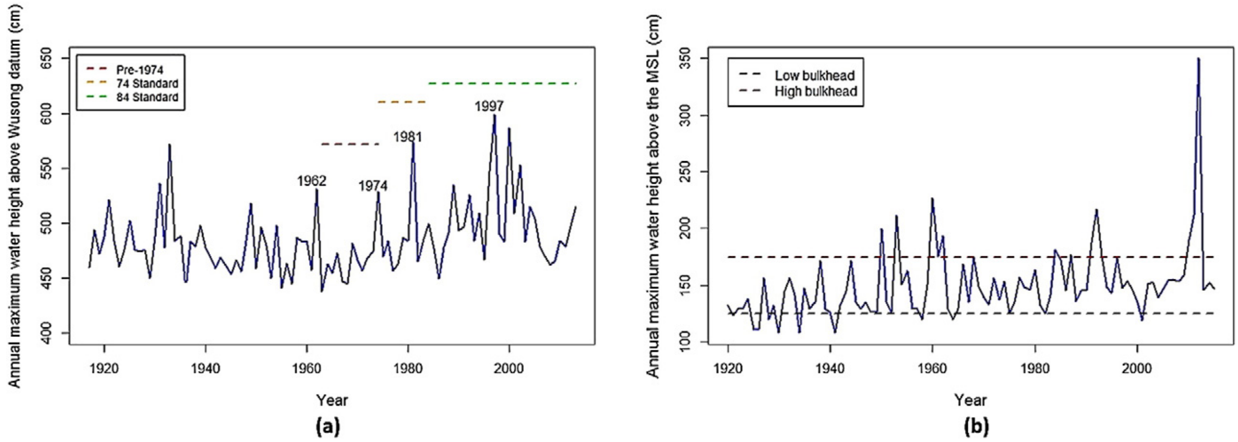

Fig. 9. Comparison of time series of annual maximum water levels and flood protection levels for (a) Shanghai and (b) NYC.

are within both provincial and central administrations in China. Initiatives from direct-controlled municipalities are usually given priority in evaluation with a very high chance of being approved by the central government (Gupta, 2007). In addition to the higher level of autonomy in decision making, other governance factors may be considered regarding Shanghai's fast responses to extreme floods. For example, both the central and local governments are aligned, allowing them to achieve consensus on extensive efforts needed to protect the city due to its most significant economic position in China (Wei and Leung, 2005; Yin et al., 2011); also, rapid economic growth in Shanghai and China during the past 30 years provided adequate funding for large-scale infrastructure development including the implementation of flood protection (Zhang, 2003). Further studies are needed to understand these and other governance factors.

London (Thames Barrier), Rotterdam, Amsterdam (dike-rings) and New Orleans (surge barrier) are all good examples showing that cities in democratic states invested in large flood protection infrastructure (Sayvetz, 2015). The construction of these projects was strongly motivated by significant public interests and political concerns over flood defense (Gilbert and Horner, 1984; Hanson et al., 2011; Sayvetz, 2015). NYC may learn from the experience of these cities. For NYC, the multiple jurisdictions of the city, the state and federal government present a challenge to implementing measures effectively to mitigate climate-related risks (Rosenzweig et al., 2011; McArdle, 2014).

Although Hurricane Sandy (2012) caused tremendous losses to NYC, on the positive side, it provided a "focusing event" (Kingdon, 1995) that taught or reminded the policy makers and the public of the importance of protecting the city and reducing its flood vulnerability (similar to the role played by the devastation 1953 flood that stimulated construction of the Thames Barrier, see Sayvetz, 2015). Discussions about possible flood protection strategies have since engaged a range of stakeholder groups and implementation of some plans made in response to Sandy has begun (SIRR, 2013; Aerts et al., 2014; Rosenzweig and Solecki, 2014). For example, the first phase of the "Big U" project, a proposed coastal protection system for lower Manhattan, is about to be implemented (details can be found: http://www.rebuildbydesign.org/our-work/all-proposals/winning-projects/big-u). Other proposals for Long Island, the Bronx, and Staten Island are in the process of design and discussion. The city also put efforts into other aspects including issuing draft design guidelines aimed at reducing flood risk for City-funded capital projects (NYC's Mayor's Office of Recovery and Resilience, 2017). In addition, new public and private hospitals no longer can be located within the flood zones. The city initiated the Resilient Neighborhoods in which the Department of City Planning is working closely with community groups to develop targeted strategies to increase building and neighborhood resiliency to coastal flooding through zoning and land use changes. Although NYC is moving forward with these and other strategies and initiatives to enhance its flood resilience, over time the memory of Sandy could decay (Viglione et al., 2014) suggesting the need to institutionalize these new mechanisms for long-term resilience planning and updating in addition to relying on focusing events.

Long-term flood risk can be assessed through observed historical data and physically based modeling that accounts for the effect of climate change and urban development (Lin et al., 2016; Lin and Shullman, 2017). The lessons from Sandy imply that flood-prone coastal megacities may need to protect their coastline with at least local-scale measures (e.g., flood walls, levees) even if few extreme events appear in the historical record because rare events can still represent unacceptable risk for densely populated areas. Without proper protection in advance, many other coastal locations can be expected to experience disastrous flooding from historically-rare events as occurred with Hurricane Sandy (e.g., Tampa Florida, see Lin and Emanuel, 2016).

The comparison of the two cities also provides insights into future flood resilience projects. The temporal variation of the flood risk needs to be evaluated and considered in projects related to coastal resilience. The strengthening of flood protections in Shanghai suggests that these measures may not be sufficient to prevent future flooding as the flood risk increases with time. Shanghai's current coastal flood protection does not take into account the dynamics of future climate and sea level (Gu, 2005). Previous studies show that around half of the length of current sea walls in Shanghai may be overtopped by 2100 due to climate-driven sea level rise and land subsidence (Wang et al., 2012). However, it seems that policy makers may believe that a sea wall is high enough, perhaps because they do not pay sufficient attention to increasing flood risk until disaster strikes, and are reluctant to "overspend" on measures that are effectively irreversible, e.g., the Three Gorges Dam (Lempert et al., 2012; Reeder and Ranger, 2011). However, this reluctance may result in more costly and less efficient actions later: after individual extreme events, policy makers have sometimes recognized the existing inadequacies and reconstructed flood protection (see Section 3.2 for evidence). A more efficient and economical way of protection would incorporate the time-variant hazard systematically into the design process before construction is initiated. As the sciences progress and projections of climate change and sea level rise change, designs can be updated: e.g., a "flexible adaptation pathway" is needed to allow efficient adjustments over time to reflect the new climate risk information (Solecki, 2012; Rosenzweig and Solecki, 2014). Specifically, the flood protection system may be designed and constructed with sufficient flexibility to permit future modifications to ensure that the protection height is always above the level of the acceptable risk. For example, a dynamic design of a sea wall, which allows incremental increases of its height as the flood risk increases over time, is more flexible

than a typical design of a wall with a fixed height. The economically optimal height can also be updated given new risk information (Lickley et al., 2014).

Furthermore, the surrounding environment and eco-system should be considered when attempting to improve coastal flood resilience. Future flood protection measures should be incorporated into the larger framework of urban resilience, harmonizing them with the surrounding environment and ecosystem. Thus, flood protection design should not only shield the city against coastal flooding but also enhance the public realm for a city's diverse communities. For example, the aim of the winning proposals in the federal competition "Rebuild by Design"[6] is not only to protect the region from flooding but also to offer social benefits to the local communities. Other studies have also discussed the benefit of large-scale, nature-based protection such as marshes/wetlands to reduce the impact of storm surge flooding (Temmerman et al., 2013; Orton et al., 2015). These proposals and ideas may point future directions to coastal megacities around the globe about how to take into account the surrounding environment, eco-system and sustainability in coastal resilience projects.

5. Conclusions

Coastal megacities, such as NYC and Shanghai, face an increasing threat from flooding in the future. However, the wealthier NYC seems to be less well protected than Shanghai. In this article, we have examined and suggested possible explanations for this phenomenon in terms of risk factors and history of past extreme events. Extreme value analysis reveals that the return period of the most extreme flood events for Shanghai (i.e., Typhoon Winnie) is much shorter than that for NYC (i.e., Hurricane Sandy). Future modeling studies should include both direct human factors influencing subsidence as well as climate change effects (e.g., sea level rise and possible storm climatology change) in assessing future flood risk. Shanghai is highly vulnerable to flooding, illustrated by the DEM and maximum potential inundation extent. Although large portions of NYC were not inundated during Sandy, some wealthy sections (e.g., Lower Manhattan) with critical infrastructure located in low-lying or landfill areas were inundated. The city is highly vulnerable to flooding especially when network effects are considered. In contrast to NYC, Shanghai has witnessed a rapid urban expansion, population increase, and economic growth in recent decades. The highly dynamic change and highly concentration of exposure in low-lying areas (the majority of Shanghai is low-lying) may contribute to Shanghai's high motivation toward flood protection. Furthermore, actions to upgrade flood protection were closely preceded by past extreme events in Shanghai. In contrast, although past flooding experience triggered some protection initiatives in NYC, extreme flooding events before Hurricane Sandy did not motivate government to act comprehensively. The differences in governance in the two cities may have also played a role in their different responses to past flood events. More comprehensive studies need to be done through interviews, historical archival and literature review to understand the effects of institutional governance on coastal protection measures for coastal megacities.

Policy makers should consider the temporal variations of flood hazard and coastal environment more systematically in planning long-term coastal resilience projects for coastal megacities. Optimal levels of protection can be explored at both the city level (sea wall) (Dupuits et al., 2017) and the individual home level (building retrofit) (Xian et al., 2017). Behavioral understanding should also be incorporated in both city-level policy and individual-level flood protection/adaptation decisions (Kunreuther and Weber, 2014; Shao et al., 2017c). Transnational governance developed through international collaborations among cities and other subnational units may facilitate coastal protection projects through sharing of knowledge and pooling of experience.

[6] "Rebuild by Design" include "Big U" for lower Manhattan, 'Hunts Point Lifelines" for Bronx, "Living Breakwaters" for Staten Island, and "Living with the Bay" for Long Island (for details: http://www.rebuildbydesign.org/our-work/sandy-projects).

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.scitotenv.2017.07.229.

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